

Temperature Oscillation in a Loop Heat Pipe with Gravity Assist

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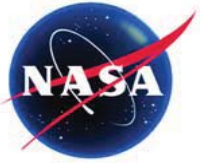
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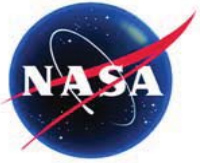
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**Spacecraft Thermal Control Workshop, The Aerospace Corporation
El Segundo, California, March 25-27, 2014**



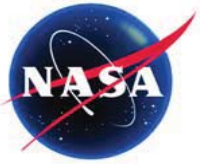
Outline

- **Introduction/Background**
- **A Theory for Temperature Oscillation with Gravity Assist and High Control Heater Power Requirement**
- **ICESat-2 ATLAS LTCS TV Test Results**
- **Summary and Conclusions**



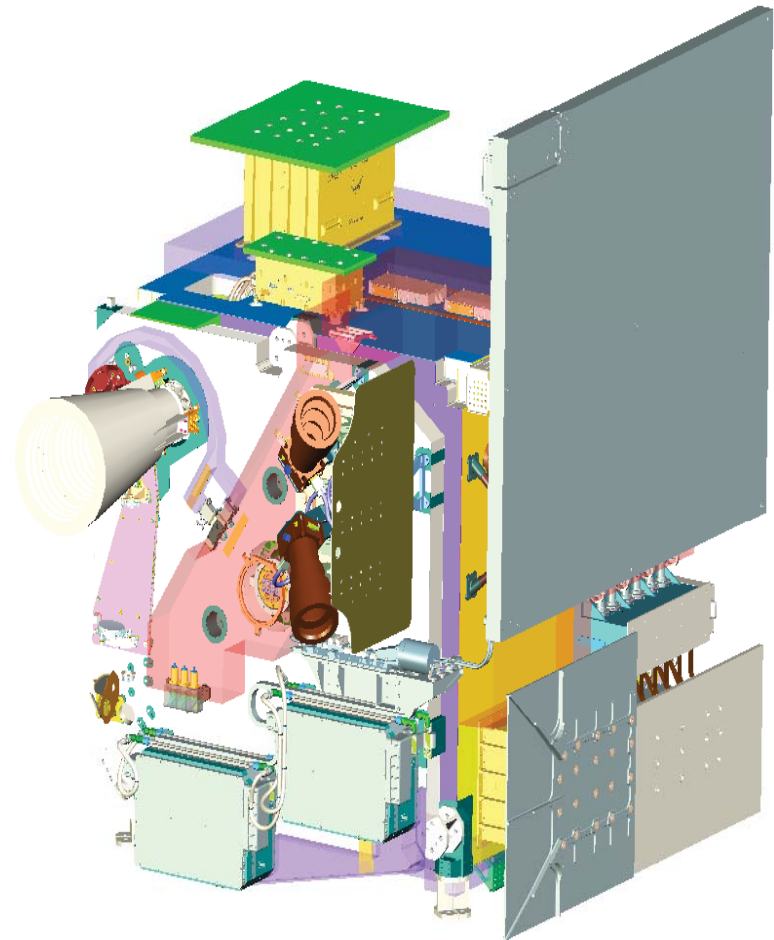
Introduction

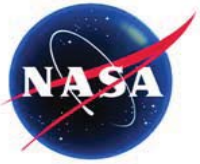
- **During ICESat-2 ATLAS LTCS TV testing, the laser mass simulators could not be controlled at desired set point temperatures.**
- **The LHP reservoir control heaters appeared to be under-sized despite flight analysis showing no issue.**
- **An investigation of the LHP behaviors found that the root cause of the problem was the temperature oscillation of the reservoir, which was in turn caused by gravity assist and a combination of other factors.**
- **Results of the investigation are presented.**



ICESat-2 and ATLAS

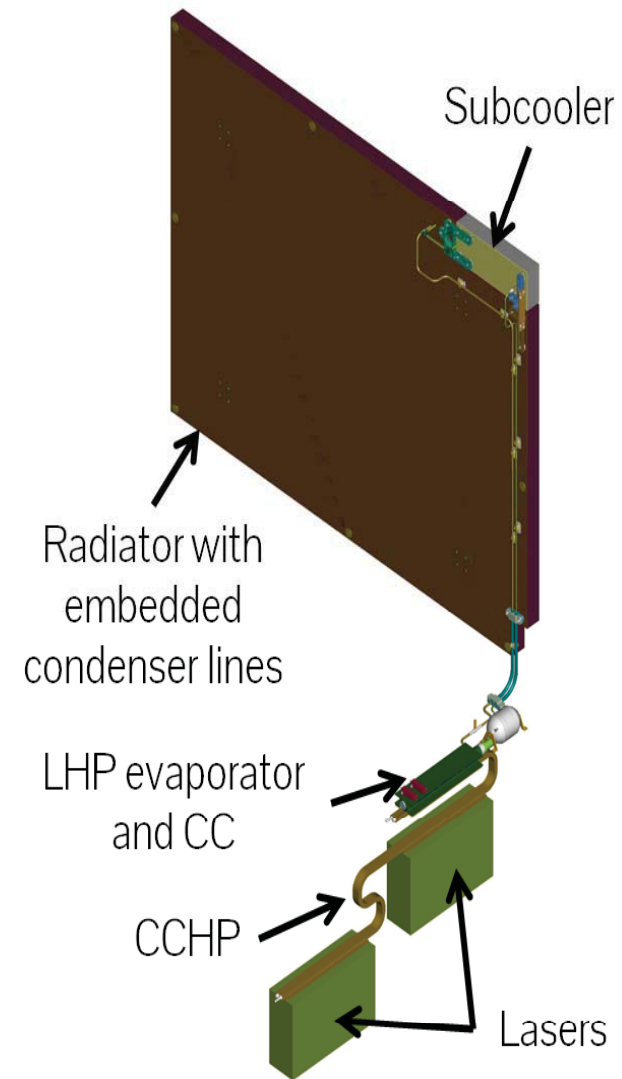
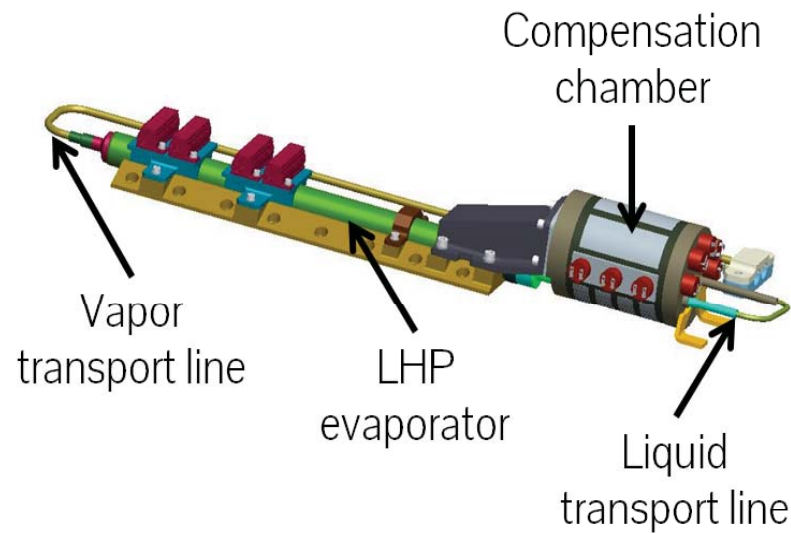
- Ice, Cloud and land Elevation Satellite-2 (ICESat-2) is an earth observing satellite expected to launch in 2016.
- The Advanced Topographic Laser Altimeter System (ATLAS) will estimate sea ice thickness and measure vegetation canopy height.
- Only one of the two redundant lasers in ATLAS will be used at a time. These lasers have stringent thermal control requirements.
- The thermal control system were designed and fabricated while the ATLAS lasers were being developed.

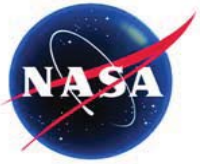




ATLAS Laser Thermal Control System (LTCS)

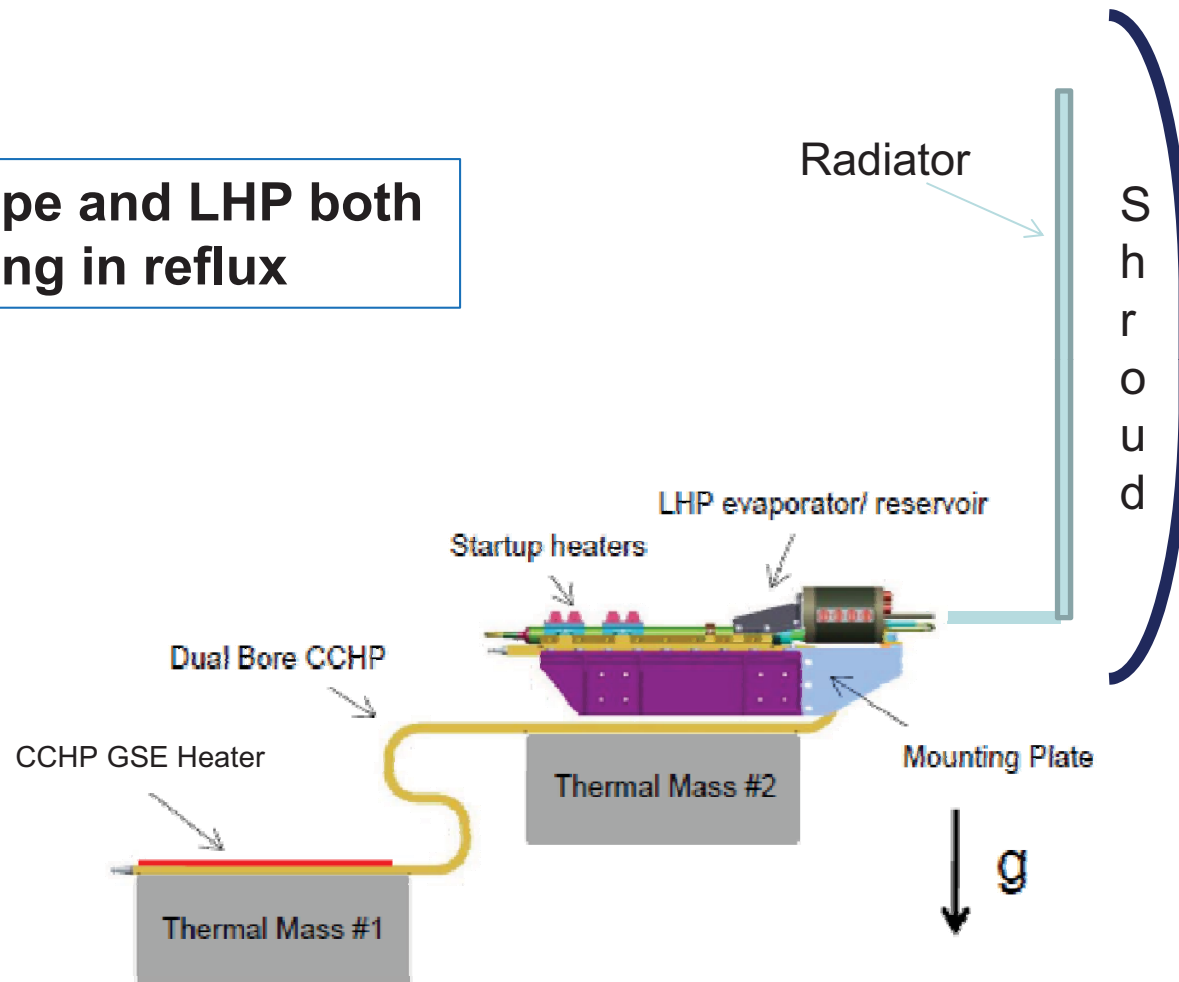
Redundant lasers are cooled via a single Laser Thermal Control System (LTCS) consisting of a constant conductance heat pipe (CCHP), a loop heat pipe (LHP), and a radiator.

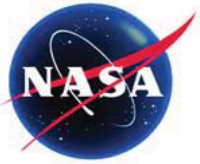




ATLAS LTCS TV Test Setup Schematic

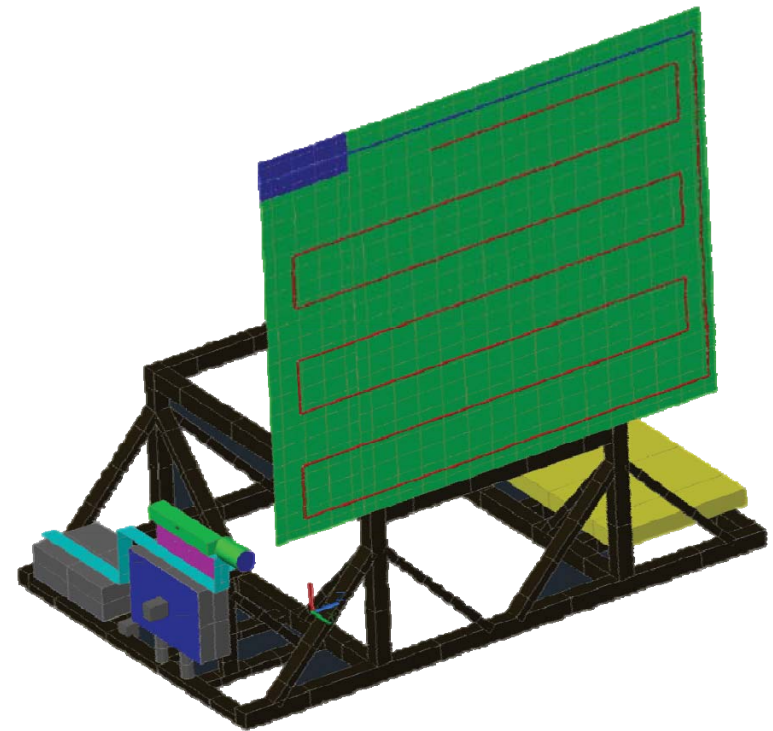
Heat pipe and LHP both operating in reflux

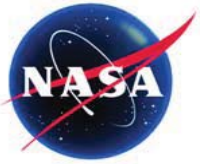




High Reservoir Control Heater Power

- In thermal balance tests, using 100% of the available heater power could not maintain the commanded reservoir temperature.
- One example:
 - 136W laser, -101 °C shroud
 - Expected Laser 1 simulator to run at +10 °C (and reservoir at +4°C) with 10.6W control power based on ATK analysis at CDR
 - Test results: Laser 1 simulator ran at -14 °C (reservoir at -24 °C) with 22W control heater power
- The reservoir displayed persistent temperature oscillations.





Theory for Temperature Oscillation with Gravity Assist and High Control Heater Power Requirement

- **A theory has been developed to explain the temperature oscillation and high control heater power requirement based on:**
 - **Mass, momentum and energy balance**
 - **LHP operating principles**
- **The theory is presented in the following order:**
 - **Thermodynamic constraints in two-phase systems**
 - **Pressure drop diagrams in LHP operation**
 - **Reservoir energy balance**
 - **Physical processes involved during temperature oscillation**
 - **Conditions leading to persistent temperature oscillation**
 - **Relevant ATLAS LTCS TV test data that partially verify the theory**



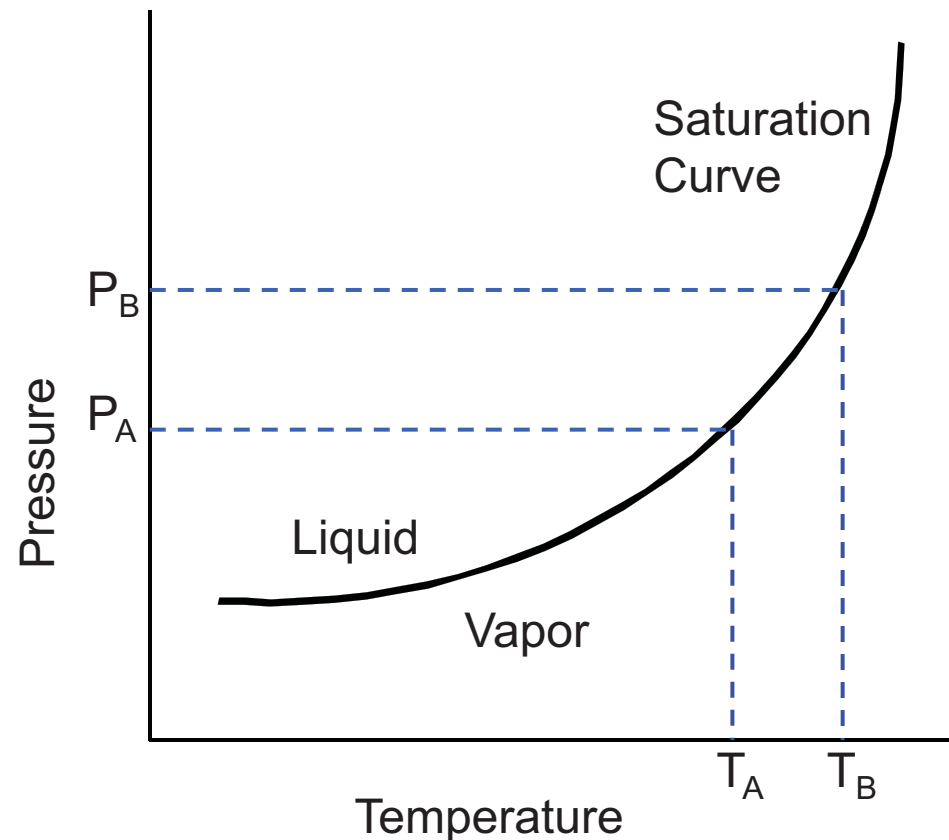
Thermodynamic Constraint in Two-Phase Systems

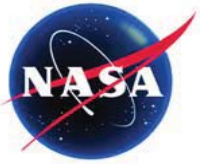
The following relation must be satisfied between any components where liquid and vapor phases coexist in thermodynamic equilibrium.

$$T_B - T_A = (P_B - P_A) / (dP/dT)$$

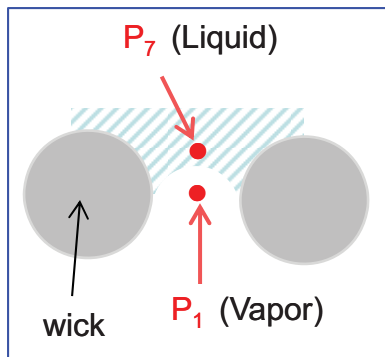
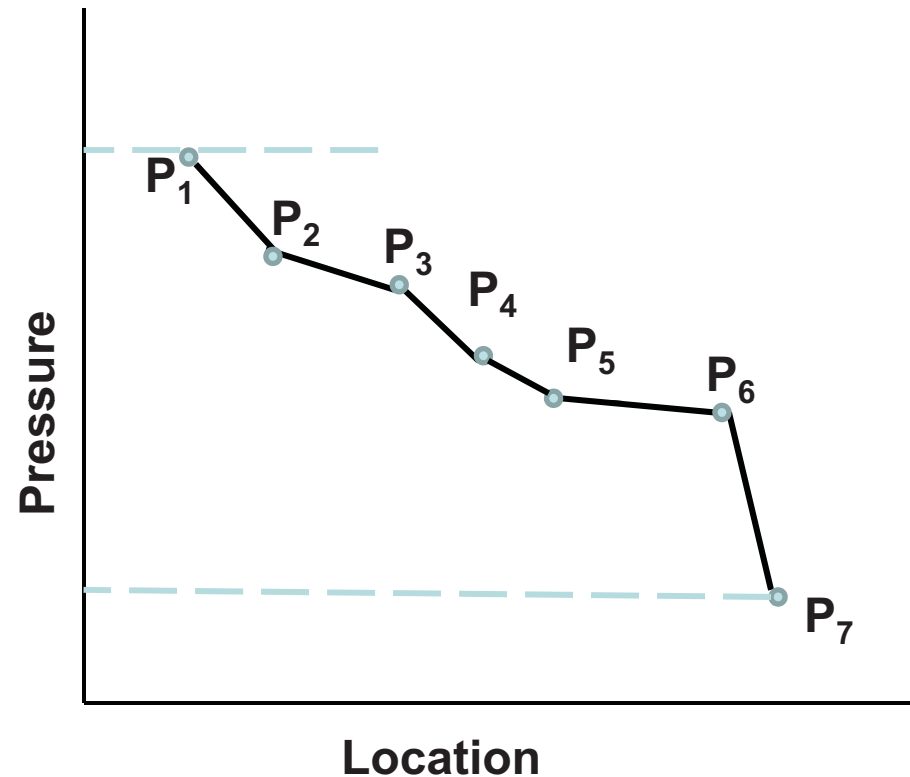
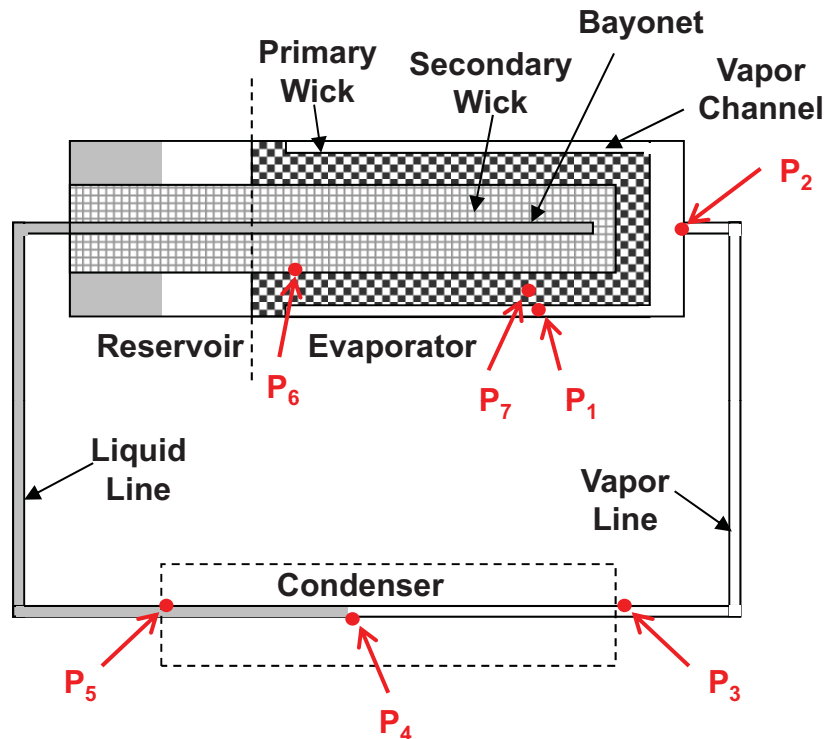
Or,

$$T_B - T_A = (P_B - P_A) (T_B \Delta v / \lambda)$$

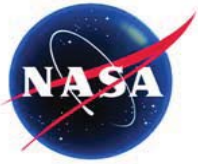




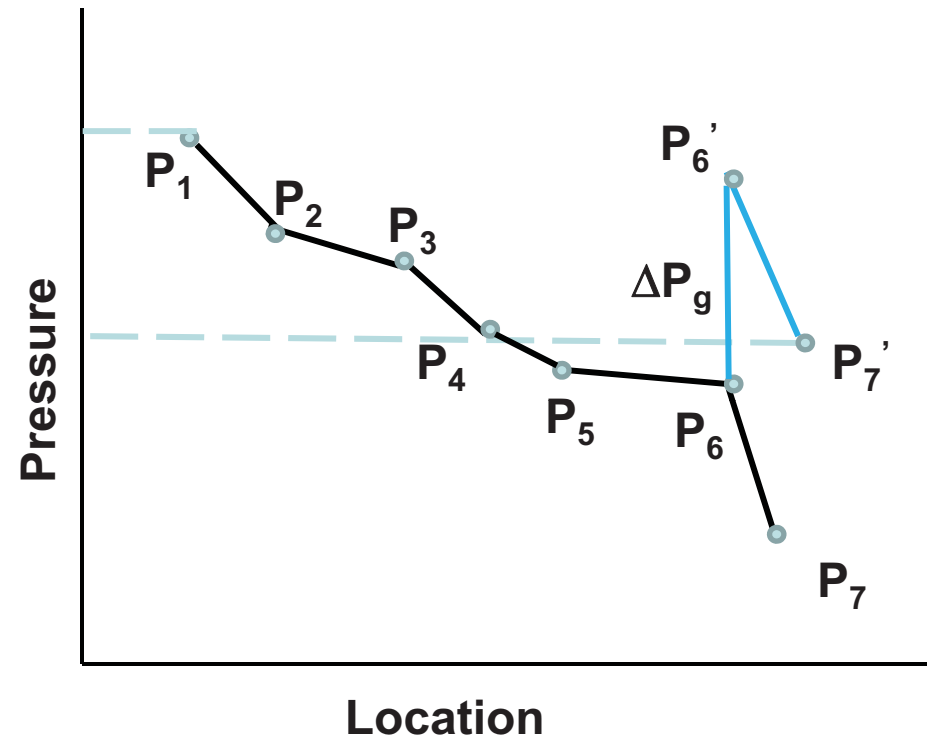
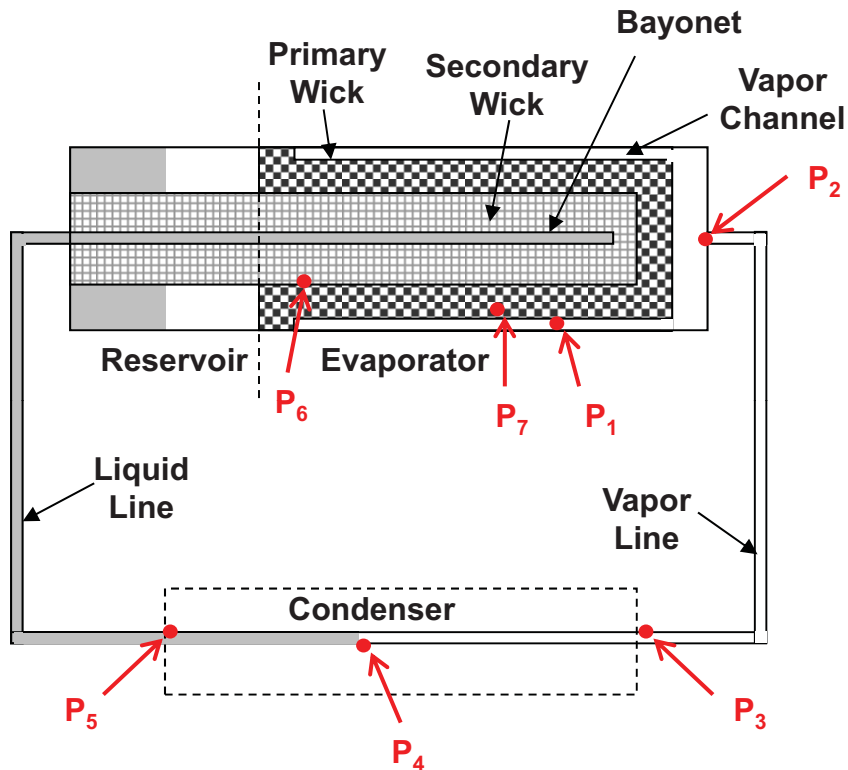
Pressure Drop Diagram in LHP Under Gravity Neutral Environment



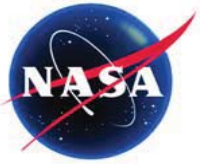
- Evaporator core is considered part of reservoir.
- P_6 is the reservoir saturation pressure.
- All other pressures are governed by P_6
- All pressure drops are frictional pressure drops.



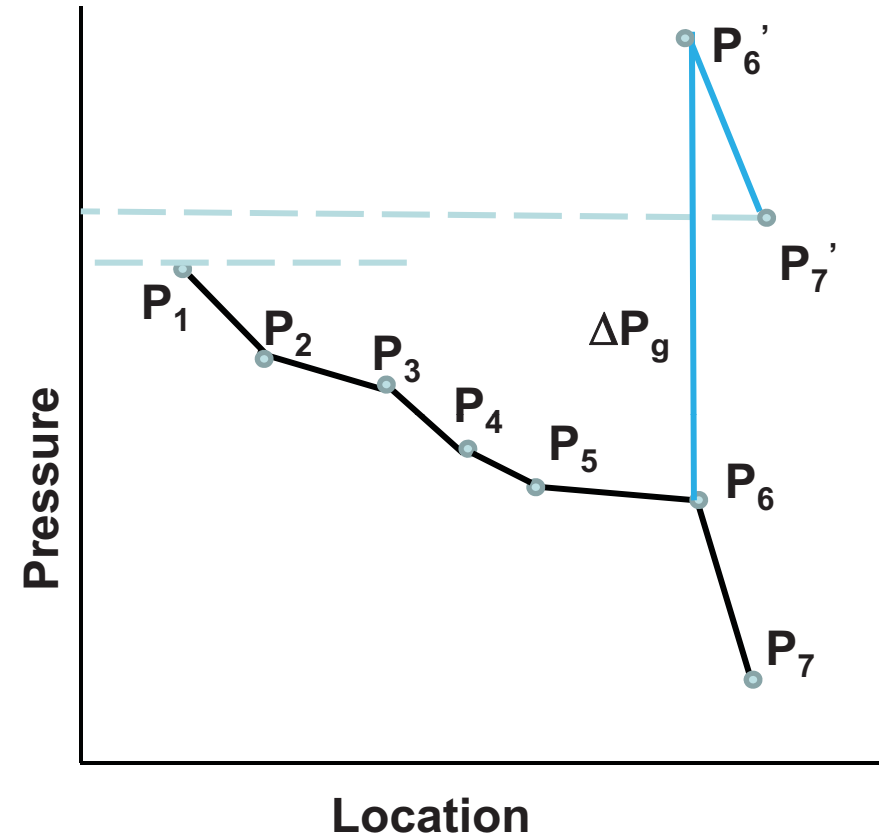
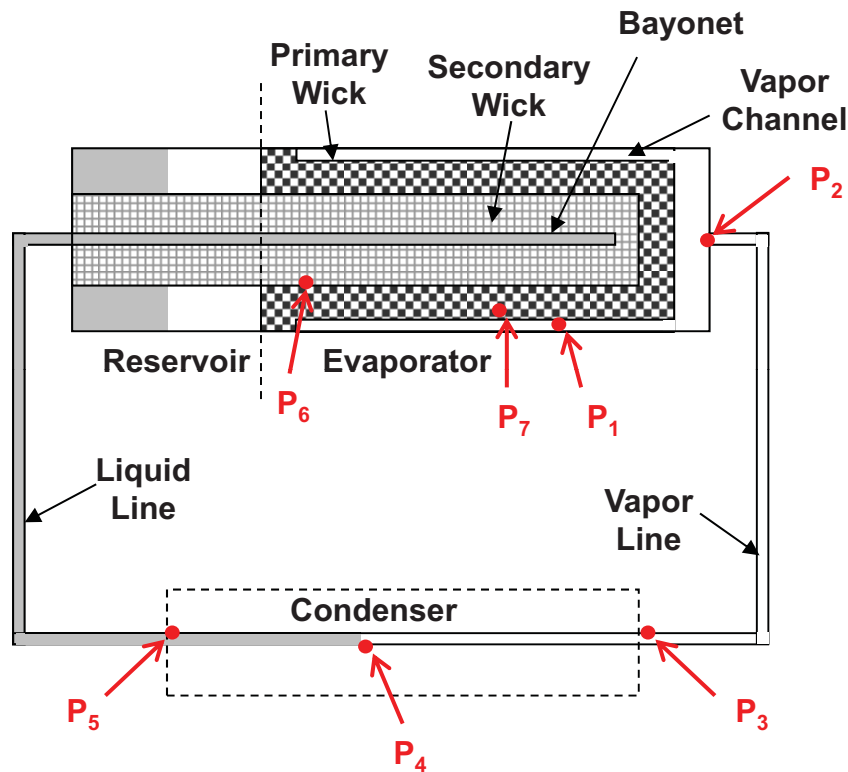
Pressure Drop Diagram in LHP With Gravity Assist



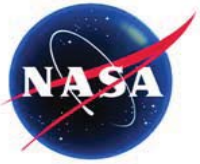
- Gravity assist raises the reservoir pressure from P_6 to P_6'
- All other pressures are governed by P_6'
- Frictional pressure drops remain the same.
- When $\Delta P_g > P_5 - P_6$ (i.e. $P_6' > P_5$), liquid will fall from the condenser to the reservoir.,



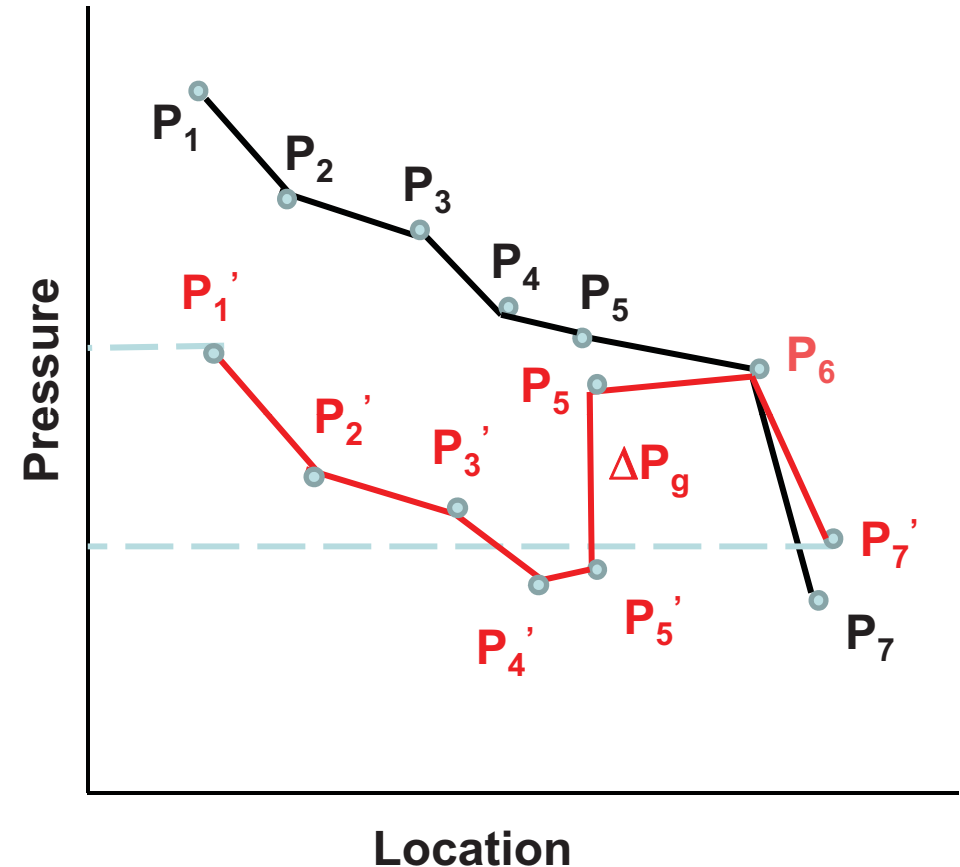
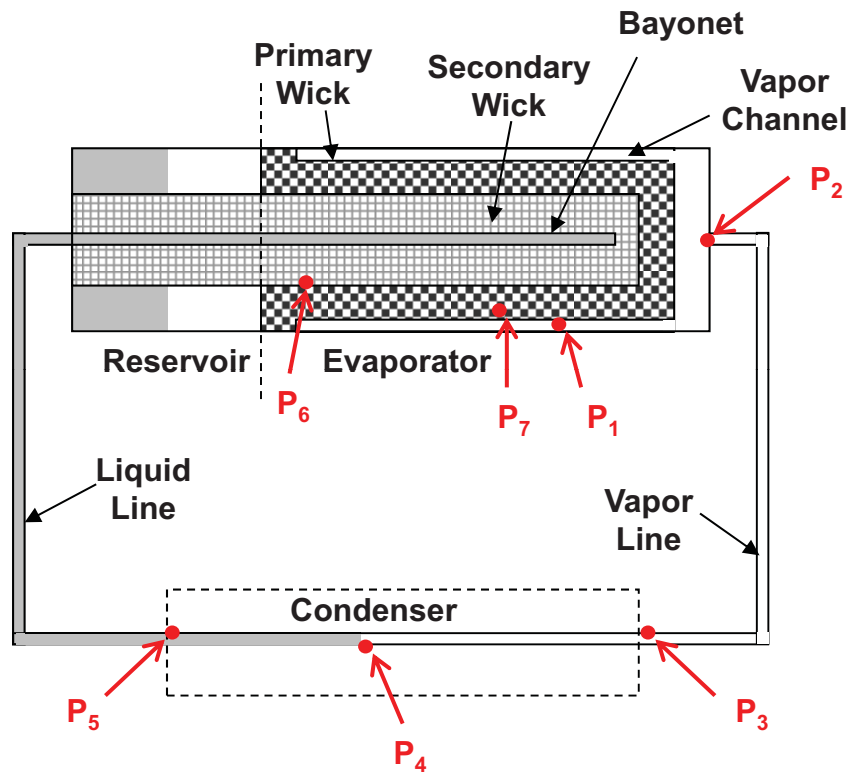
Pressure Drop Diagram in LHP With Gravity Assist



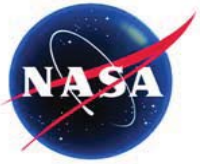
- Gravity assist raises the reservoir saturation pressure from P_6 to P_6' .
- All other pressures are governed by P_6'
- Frictional pressure drops remain the same.
- When $P_7' > P_1$, liquid will be pushed into evaporator vapor grooves.



Pressure Drop Diagram in LHP With Gravity Assist and Liquid Reverse Flow



- Absolute pressures with a reverse liquid flow are shown in red.
- The reservation pressure is at P_6 , which governs all other pressures.
- $P_6 - P_5$ = frictional pressure drop due to reverse liquid flow.
- Reverse liquid flow works against gravity, thus $\Delta P_g < 0$.

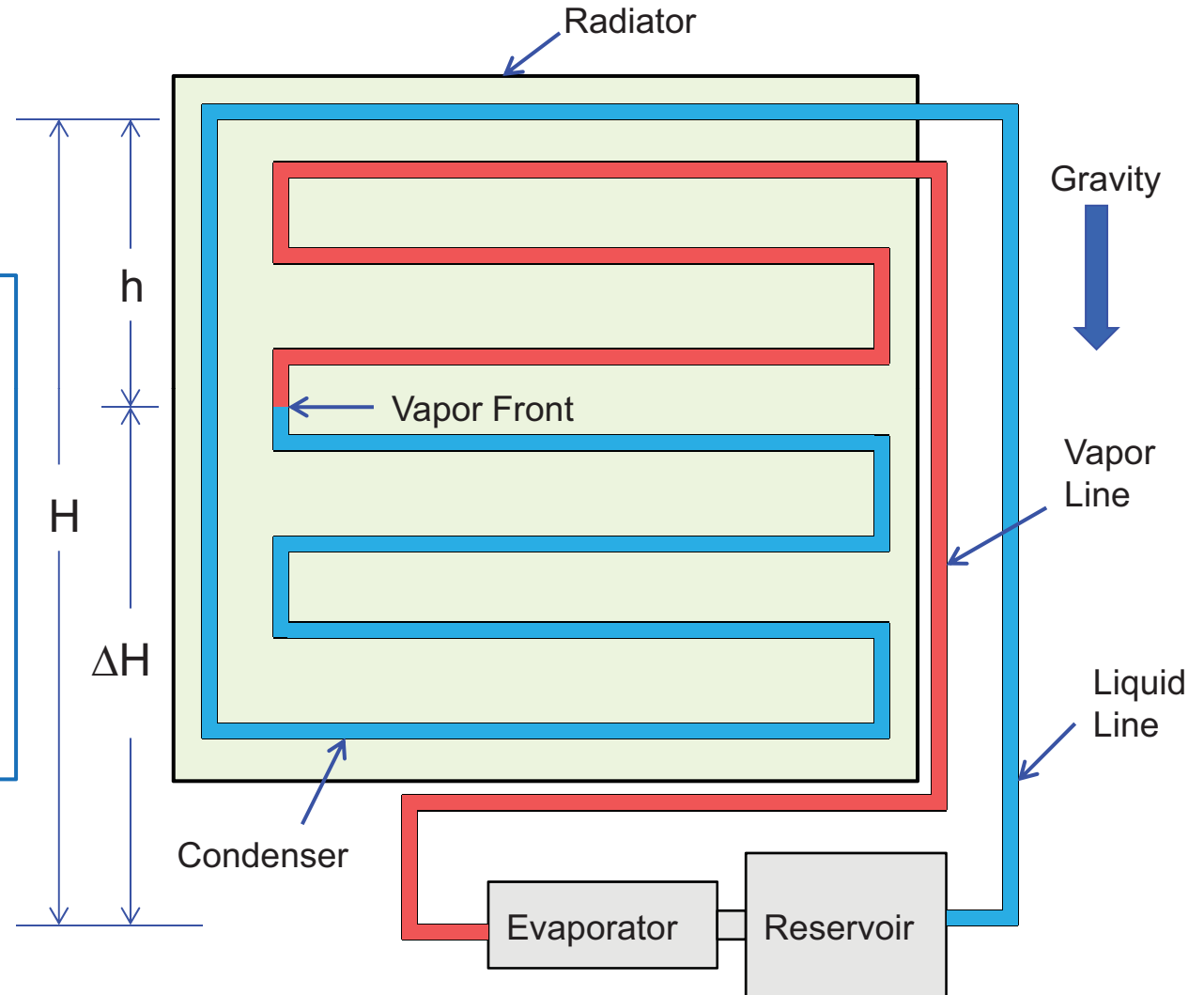


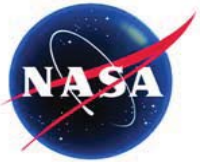
Gravity Pressure Head with a Vertical Radiator

$$\Delta P_g = (\rho_l - \rho_v)g \Delta H$$

$$\Delta H = H - h$$

ΔH and ΔP_g vary
with the vapor front
position.





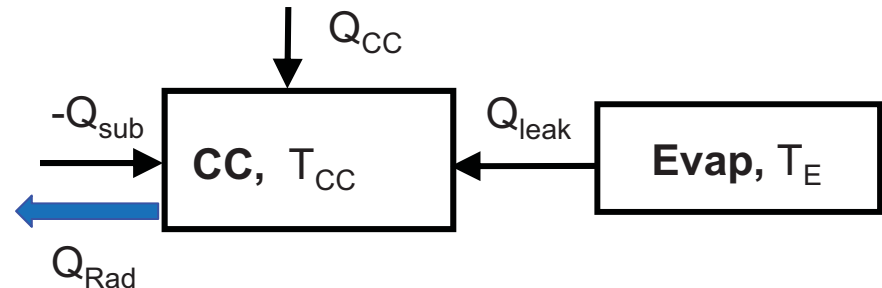
Energy Balance in Reservoir

- For steady state operation:

$$Q_{CC} = Q_{sub} - Q_{leak}$$

$$Q_{sub} = m_{liq} C_p (T_{cc} - T_{in})$$

$$m_{liq} = (Q_E - Q_{leak})/\lambda$$

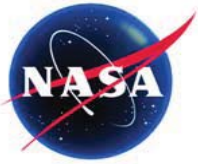


- m_{liq} is not constant during temperature oscillation.
 - m_{liq} and Q_{sub} are increasing when T_{cc} is decreasing.
 - A reverse liquid flow occurs when T_{cc} is increasing, carrying warm fluid to the condenser.
 - Q_{rad} represents additional heat leak during temperature oscillation compared to steady state.

- During quasi-steady of temperature oscillation*:

Total energy loss as reservoir temperature drops from its peak to valley =
Total energy provided by the control heater as reservoir temperature rises
from its valley to peak

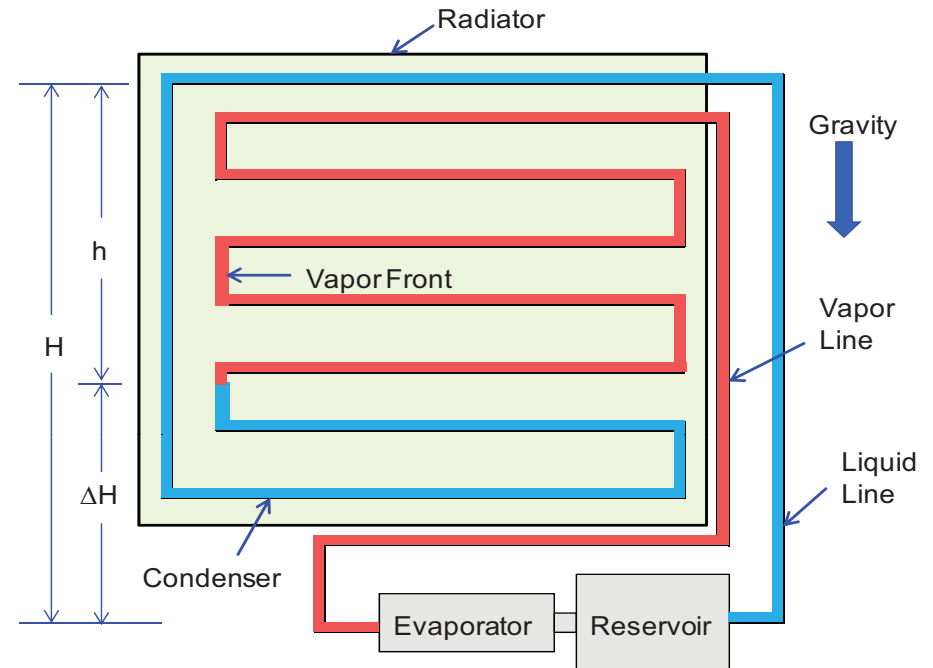
*The control heater is turned on at all times.



Physical Processes during Temperature Oscillation

Reservoir Temperature Decreasing

- Gravity causes liquid to drop from condenser to reservoir.
- With cold radiator, the liquid carries large subcooling.
- Reservoir temperature decreases rapidly.
- Thermal mass releases sensible heat, increasing heat load to evaporator.
- Vapor front inside condenser advances with increasing heat load and decreasing reservoir temperature.
- Liquid mass flow rate increases, causing reservoir temperature to drop further.
- Vapor front will stop advancing because of energy balance requirement in condenser and the decreased gravity pressure head.
- Control heater is always turned on. Reservoir temperature begins to increase.

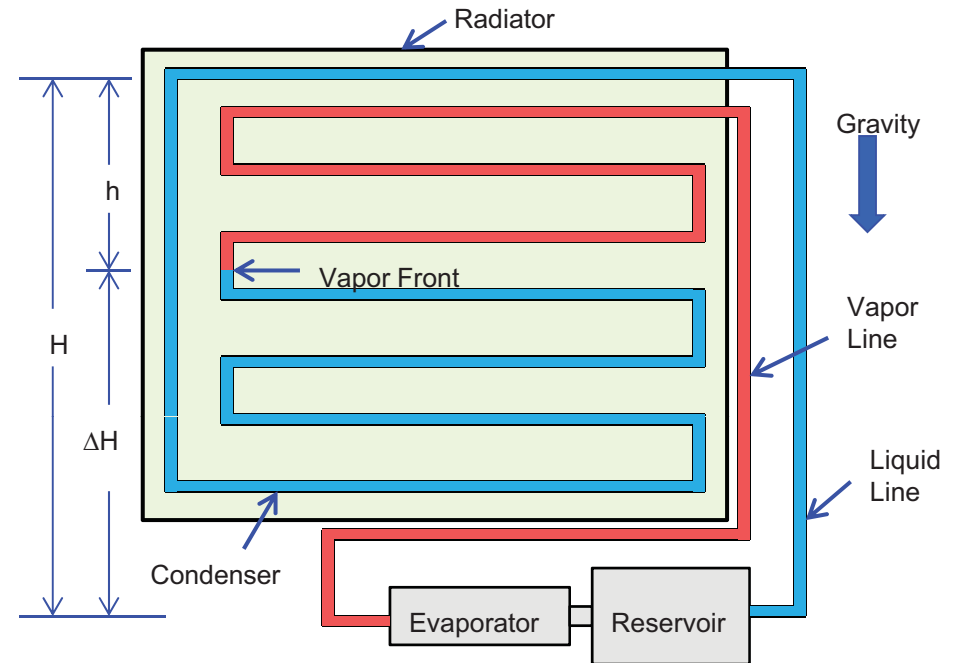


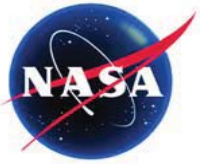


Physical Processes during Temperature Oscillation

Reservoir Temperature Increasing

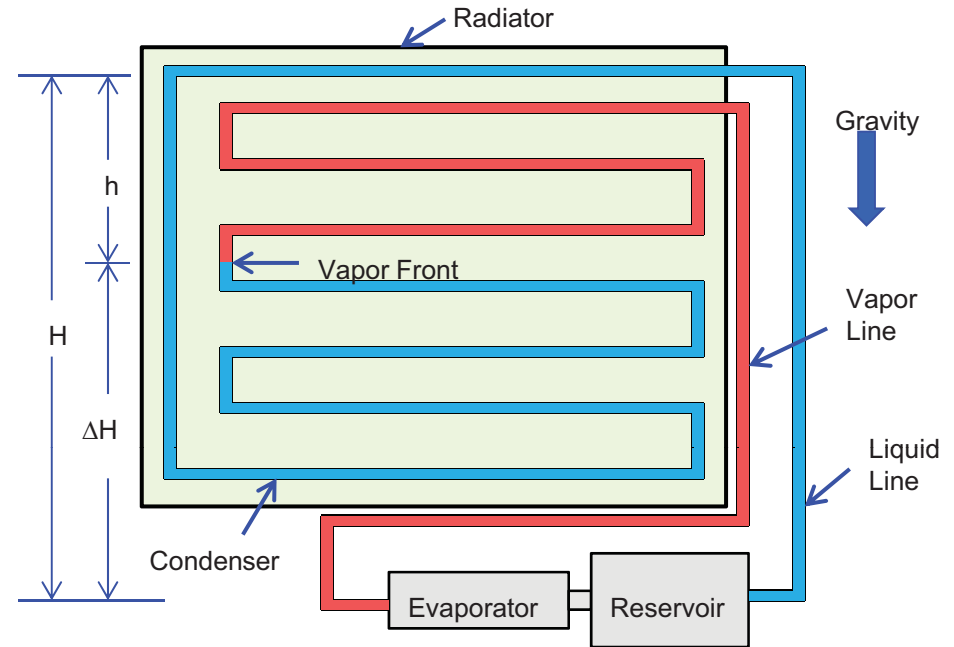
- When reservoir temperature increases, thermal mass stores sensible heat.
- Vapor front inside condenser recedes with decreasing heat load and increasing reservoir temperature.
- Control heater causes reverse liquid flow along liquid line, filling the space left by vapor front recession.
- As vapor front recedes, gravity pressure head increases, slowing down the rate of reverse liquid flow.
- Because a certain length is required to dissipate heat load from evaporator, vapor length reaches it minimum.
- Vapor front stops receding and starts advancing.
- Liquid drops from condenser to reservoir. Reservoir temperature begins to decrease, repeating the temperature oscillation.

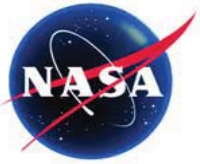




Sustaining Persistent Temperature Oscillation

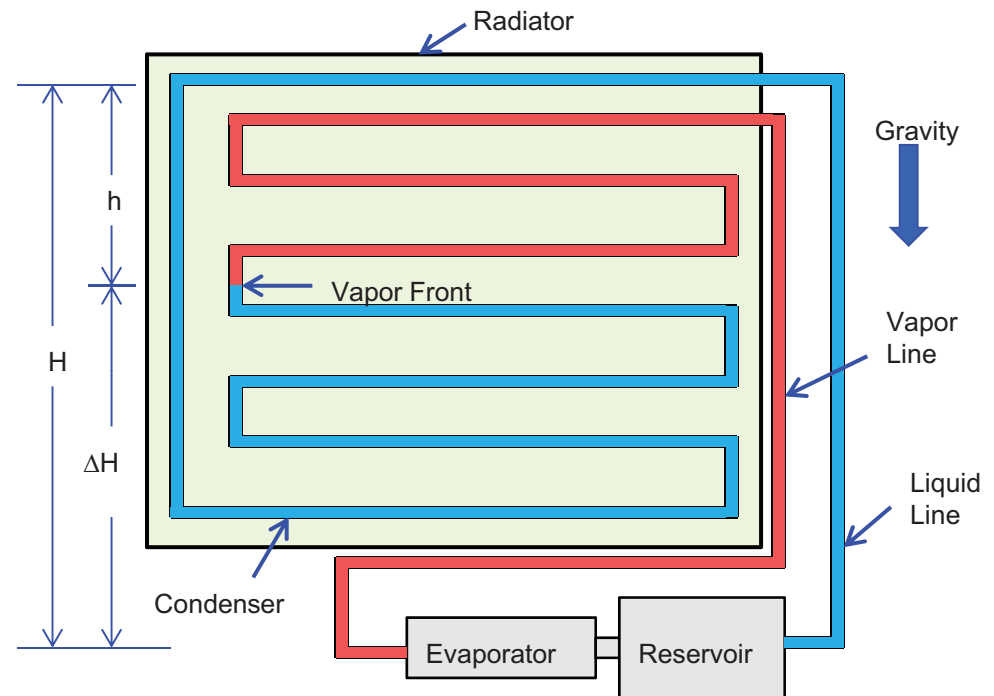
- Three driving forces sustain the persistent temperature oscillation.
 - Gravity assist
 - Liquid reverse flow
 - Continuous control heater power
- Cold radiator and large thermal mass amplify the effect of these driving forces.
- Without gravity assist, there is no persistent temperature oscillation.
- The control heater power must be sufficiently large to cause a reverse liquid flow. Otherwise, there is no persistent temperature oscillation.
- The control heater power is not large enough to maintain the reservoir set point temperature. Otherwise, intermittent “power-off” periods will stop the persistent temperature oscillation.
- Causes and effects of temperature oscillation intermingled, leading to a “circular” mechanism.

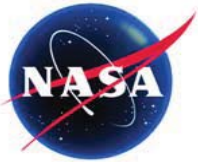




Root Cause of High Control Heater Power

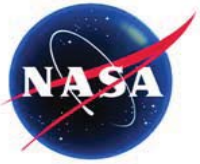
- During temperature oscillation, the reservoir is subjected to a repeated ingress of cold liquid from cold radiator.
- As the reservoir temperature is raised by the control heater, a reverse liquid flow occurs, carrying some warm liquid to the cold radiator.
- Before the reservoir set point temperature is reached, the next round of cold liquid is injected into the reservoir.
- The control heater is tuned on at all times, and its power is consumed largely to warm the reservoir toward its set point temperature which cannot be reached with existing heater power.
- The persistent reservoir temperature oscillation is the root cause of high control heater power requirement.



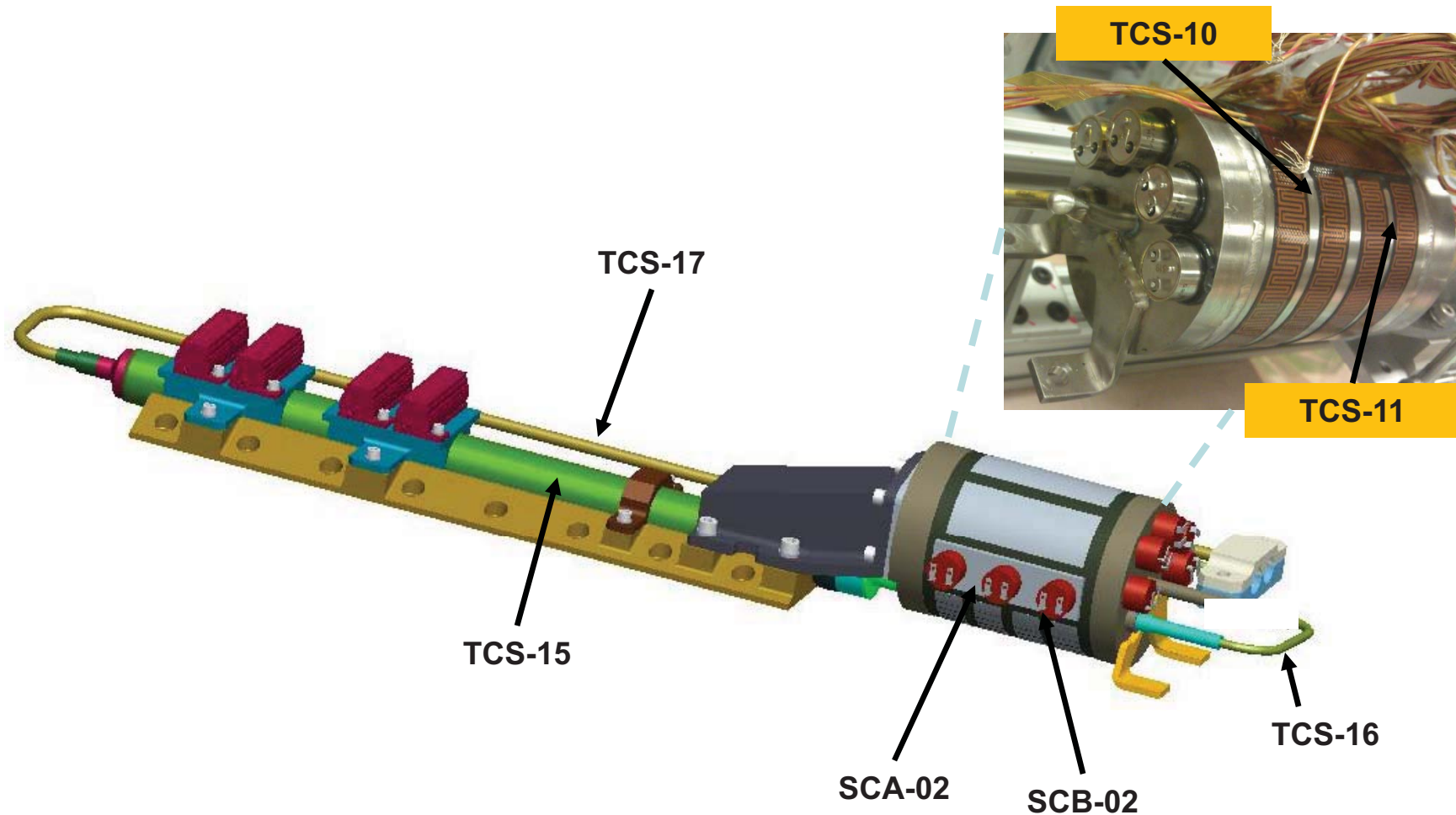


Verification of the Theory with ATLAS LTCS TV Test Data

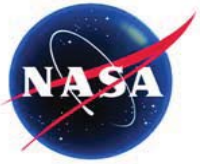
- **The theory cannot be fully verified by the existing ATLAS LTCS TV test data.**
 - No temperature sensors on the condenser itself
 - Data collection rate of once every two minutes is not sufficient to verify LHP transient behaviors
- **Some relevant data are used to provide partial verification of the theory.**
- **Verification with relevant ATLAS LTCS test data**
 - Liquid drop from the condenser to the reservoir
 - Reverse liquid flow
 - No persistent temperature oscillation without sufficient heater power
 - Effects of some parameters on temperature oscillation
- **Part of the theory that cannot be verified by ATLAS LTCS test data.**
 - Vapor front movement
 - Mass and energy balance in the reservoir
 - No persistent temperature oscillation if the reservoir set point can be maintained.



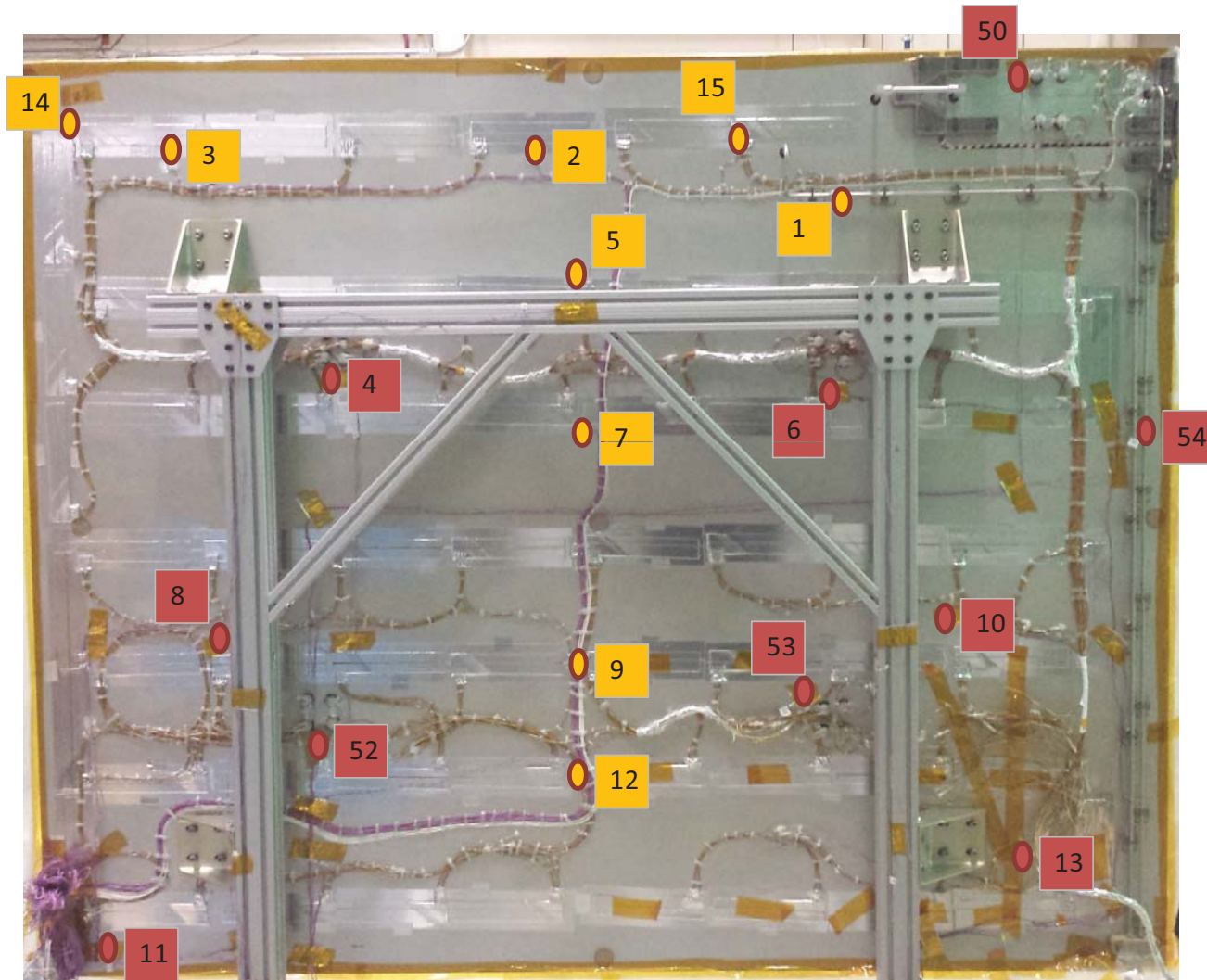
Some Temperature Sensors on ATLAS LTCS



- Only data from TCS-10 and TCS-11 were collected once every four seconds.
- All other data were collected once every two minutes.



TC Locations on Radiator

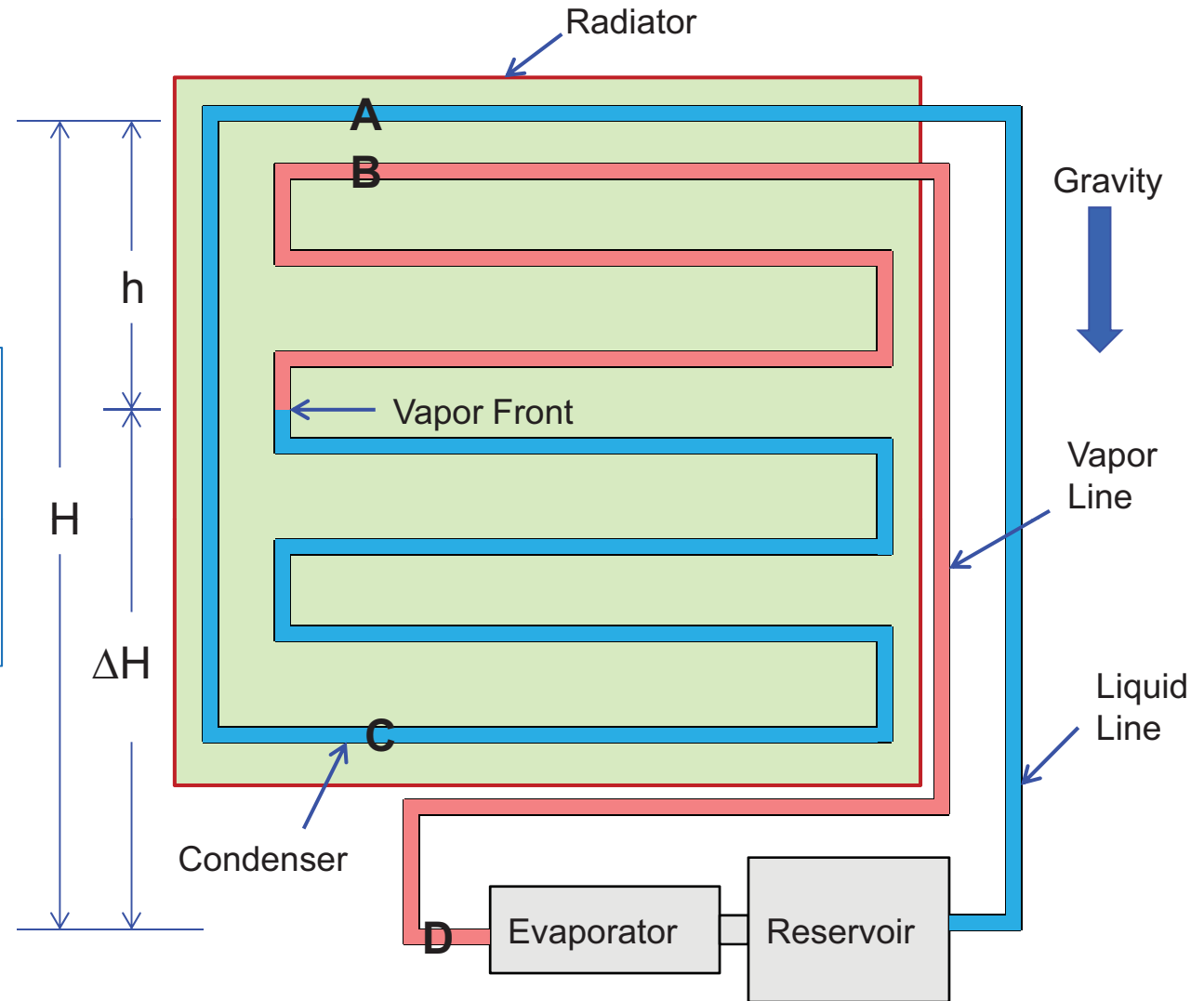
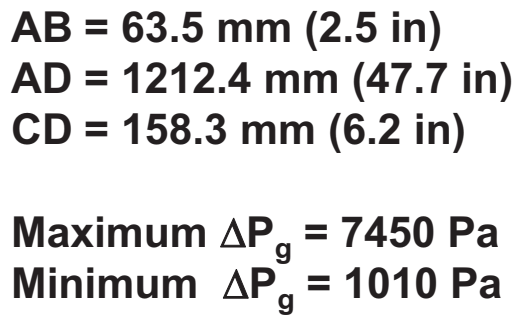


- TCs 1, 2, 3, 5, 6, 7, 9, 8, 12, 11, 14, 15 follow the condenser footprints.
- Data were collected once every two minutes.

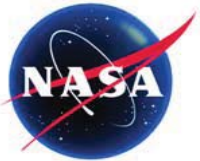


Frictional Pressure Drops (CC at -9.8°C and sink at -98 °C)

Summary of Pressure Drop (Pa)								
Component	49W	74W	109W	136W	175W	196W	249W	300W
Vapor Line	42	62	152	220	341	415	630	861
Condenser								
Two-Phase	27	60	141	267	534	696	1,342	2,137
Liquid Phase	1	2	4	7	11	14	23	32
Subcooler	0	1	1	1	1	2	2	3
Liquid Line	12	17	26	32	40	45	57	69
Capillary Pump								
Liquid Core	11	17	25	31	40	44	56	67
Wick	637	954	1,397	1,725	2,214	2,476	3,145	3,760
Vapor Grooves	42	63	92	114	146	164	208	249
Circum. Grooves	0	1	1	1	2	2	2	3
Gravitational Head	0	0	0	0	0	0	0	0
Total	772	1,178	1,840	2,398	3,320	3,858	5,465	7,181
Capillary Limit	41,552	41,552	41,552	41,552	41,552	41,552	41,552	41,552
Mass in Condenser (grams)	92.5	89.2	84.7	81.3	76.2	73	67	60
% Pcap Used	2	3	4	6	8	9	13	17



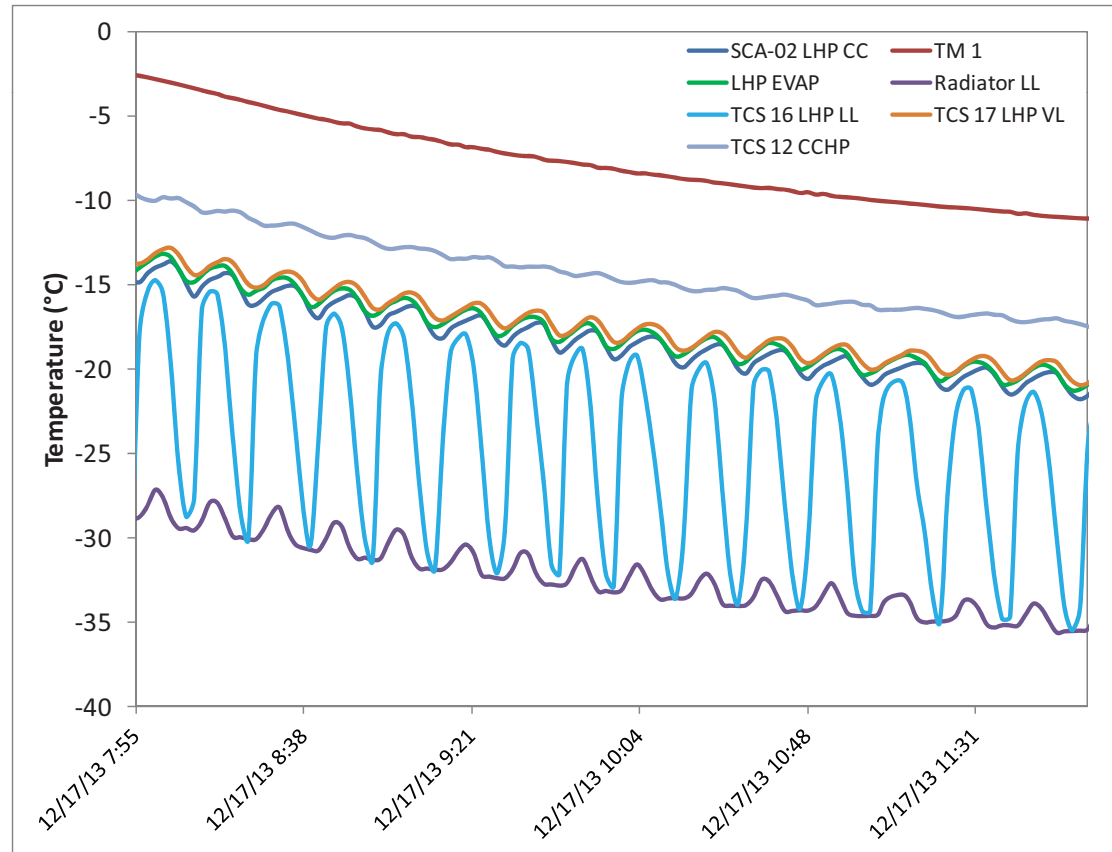
- **Analytical model predicts the frictional pressure drop along the liquid line is no more than 85Pa for powers up to 300W.**
- **According to the theory, liquid will drop from the condenser to reservoir.**

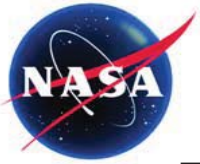


Reverse Flow During Cold Transition Test

- Test #1: Cold Transition, reservoir temperature was decreasing
- Temperatures of TCS16 and Radiator LL show that liquid drainage and reverse liquid flow did occur alternately along the liquid line.
- Oscillating reservoir temperature decreased toward its quasi-steady temperature.
- Data were collected once every two minutes.

136W to thermal mass 1, shroud at -101°C, 22W of control heater power with set points of 4°C/5°C

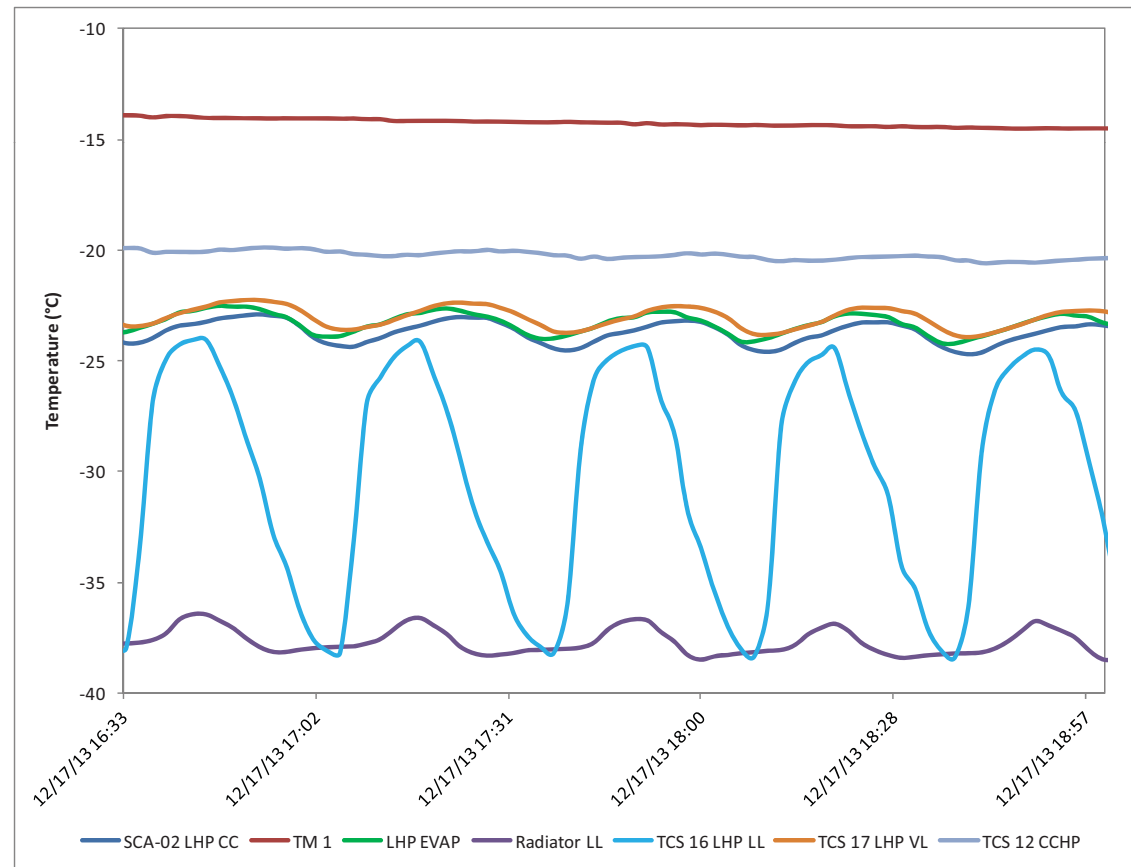


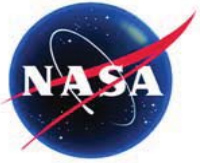


Reverse Flow During Cold Soak Test

- Test #2: Cold Soak, quasi-steady state
- Temperatures of TCS16 and Radiator LL show that liquid drainage and reverse liquid flow did occur alternately along the liquid line.
- Oscillating reservoir temperature was at a quasi-steady state.
- Data were collected once every two minutes.

136W to thermal mass 1, shroud at -101°C, 22W of control heater power with set points of 4°C/5°C

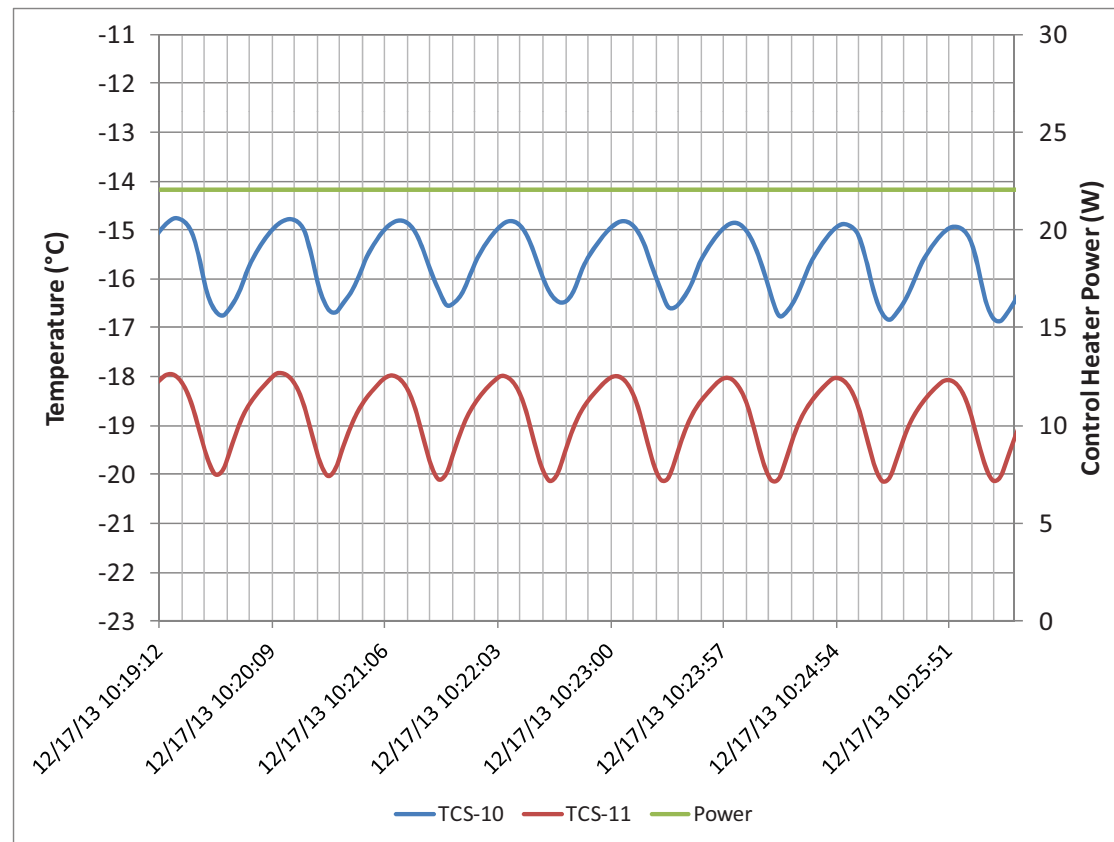


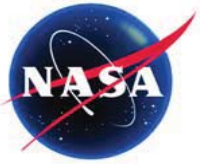


Reservoir Temperature Oscillation During Cold Transition Test

- **Test #1: Cold Transition, reservoir temperature was decreasing**
- **Data were collected once every four seconds.**
- **Reservoir temperature was decreasing.**
- **In each cycle, reservoir temperature decreased 2.1°C in 24 seconds and rose 2.1°C in 32 seconds.**

136W to thermal mass 1, shroud at -101°C, 22W of control heater power with set points of 4°C/5°C

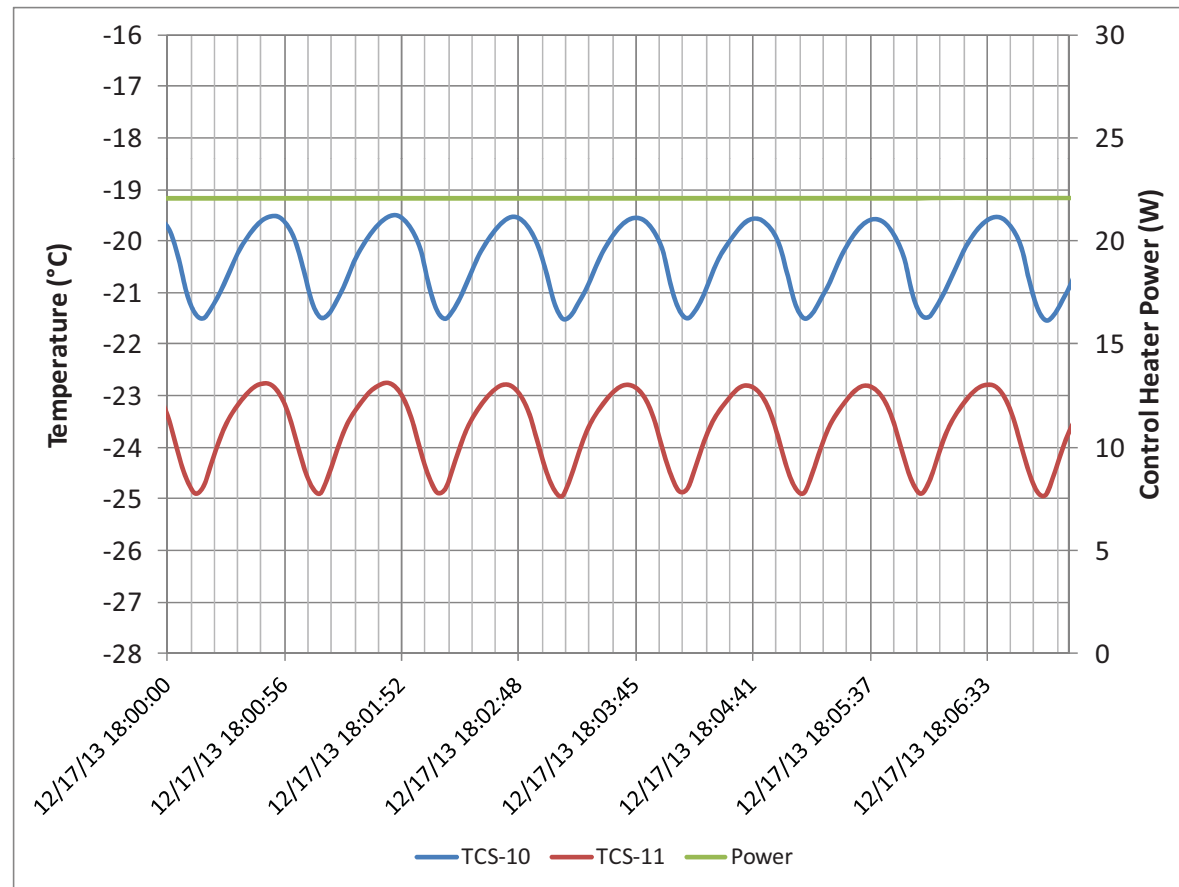




Reservoir Temperature Oscillation During Cold Soak Test

- Test #2: Cold Soak, quasi-steady state
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136W to thermal mass 1, shroud at -101°C , 22W of control heater power with set points of $4^{\circ}\text{C}/5^{\circ}\text{C}$

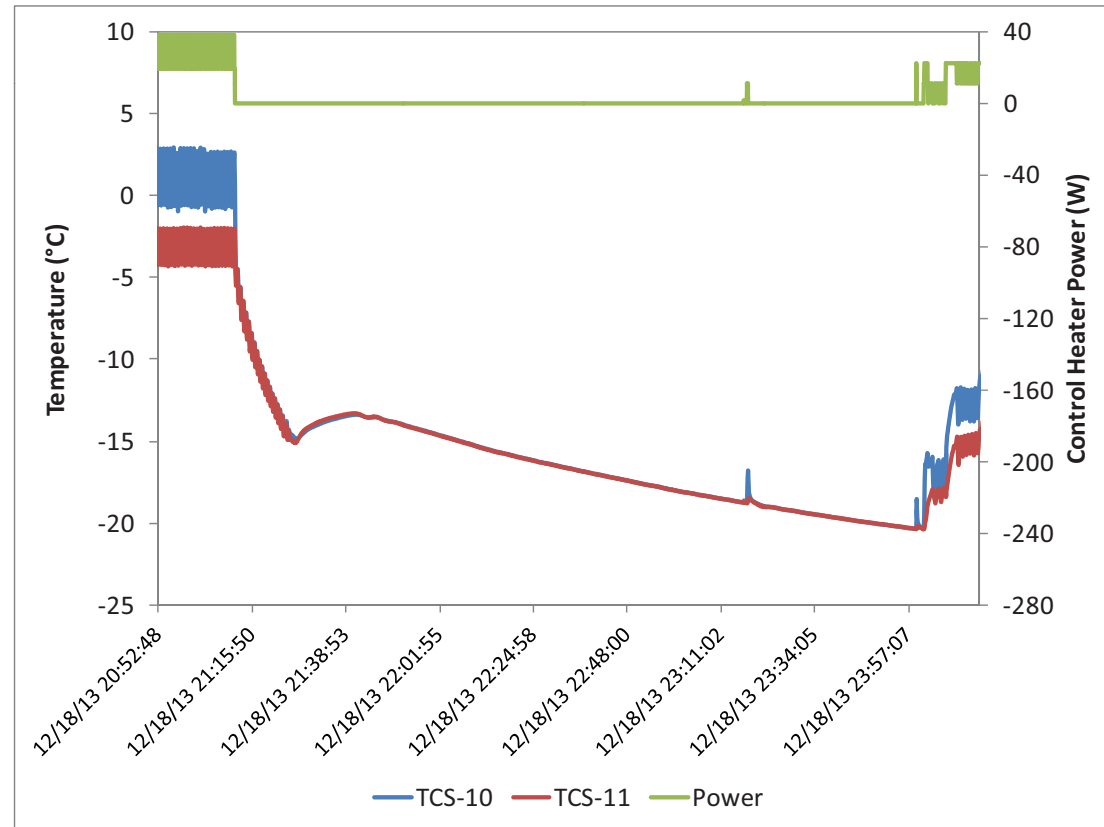


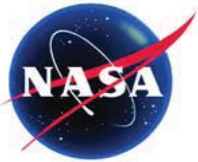


Reservoir Temperatures with and without Reservoir Heater Power

- Test #6: Cold Transition
- Reservoir temperature oscillated when control heater was turned on continuously.
- Without control heater power, there was no reverse liquid flow and no temperature oscillation.
- Data were collected once every four seconds.

196W to thermal mass 1, shroud at -78°C

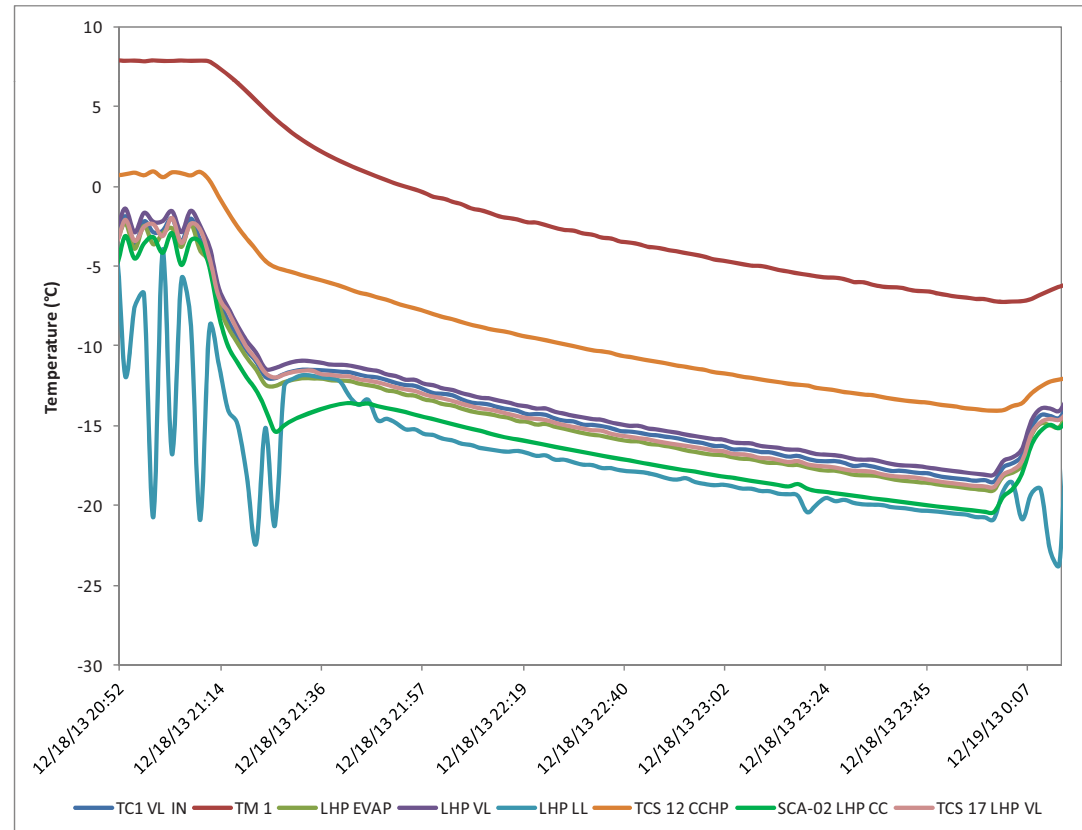


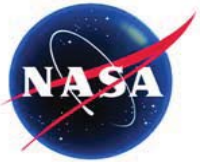


Loop Temperatures with and without Reservoir Heater Power

- Test #6: Cold Transition
- Reservoir temperature oscillated when control heater was turned on continuously.
- Without control heater power, there was no reverse liquid flow and no temperature oscillation.
- Data were collected once every four seconds.

196W to thermal mass 1, shroud at -78°C

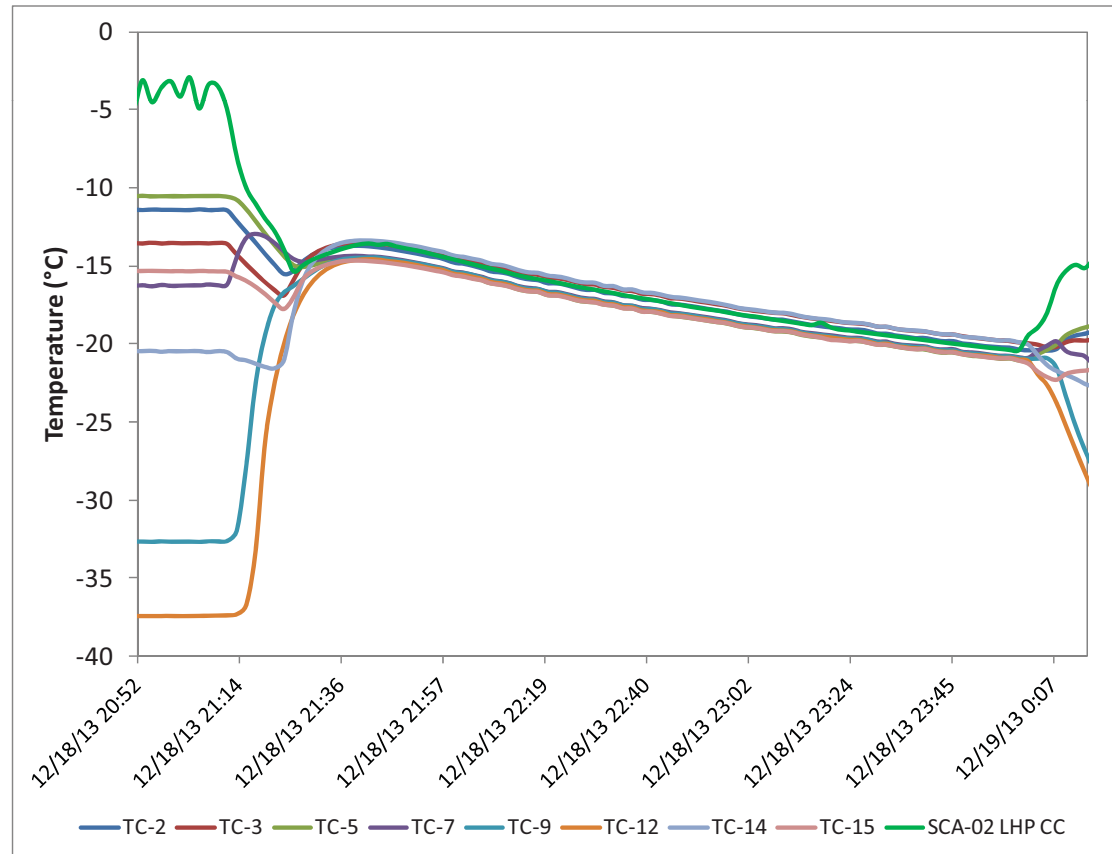


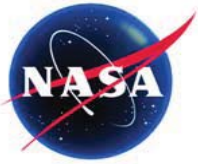


Radiator Temperatures

- **Test #6: Cold Transition**
- **No temperature oscillation on radiator at any time due to conduction and radiation effects.**
- **Reservoir was at its natural operating temperature without control heater power.**
- **Data were collected once every two minutes.**

196W to thermal mass 1, shroud at -78°C

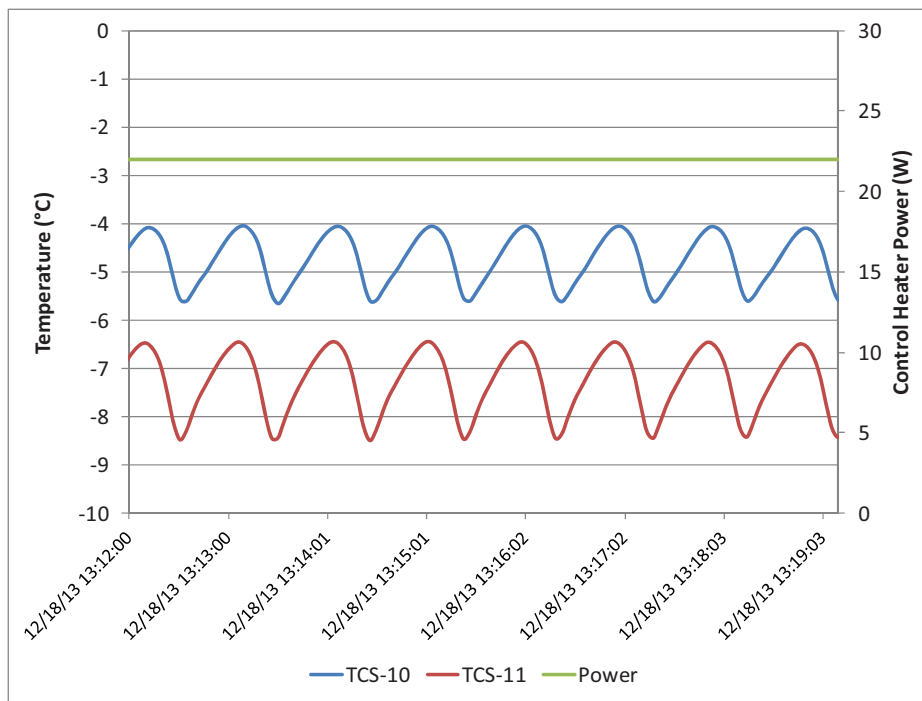




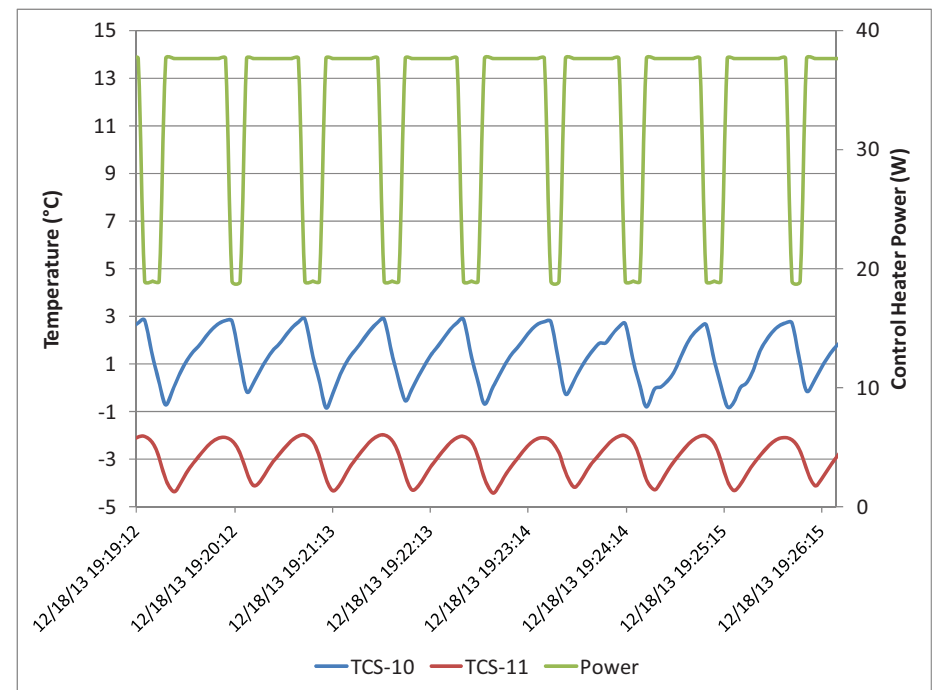
Temperature Oscillation with Various Control Heater Powers

- Test #4 and #5: 196W to thermal mass 1, shroud at -78°C , reservoir heaters set points at $-2^{\circ}\text{C}/-1^{\circ}\text{C}$
- Both heaters used TCS-11 as the control sensor.
- Increasing heater power from 22W to 38W raised reservoir temperature by 4.2°C . At 38W, one of the heaters was turned on and off. The other was on at all times.

Test #4: 22W control heater power



Test #5: 38W control heater power

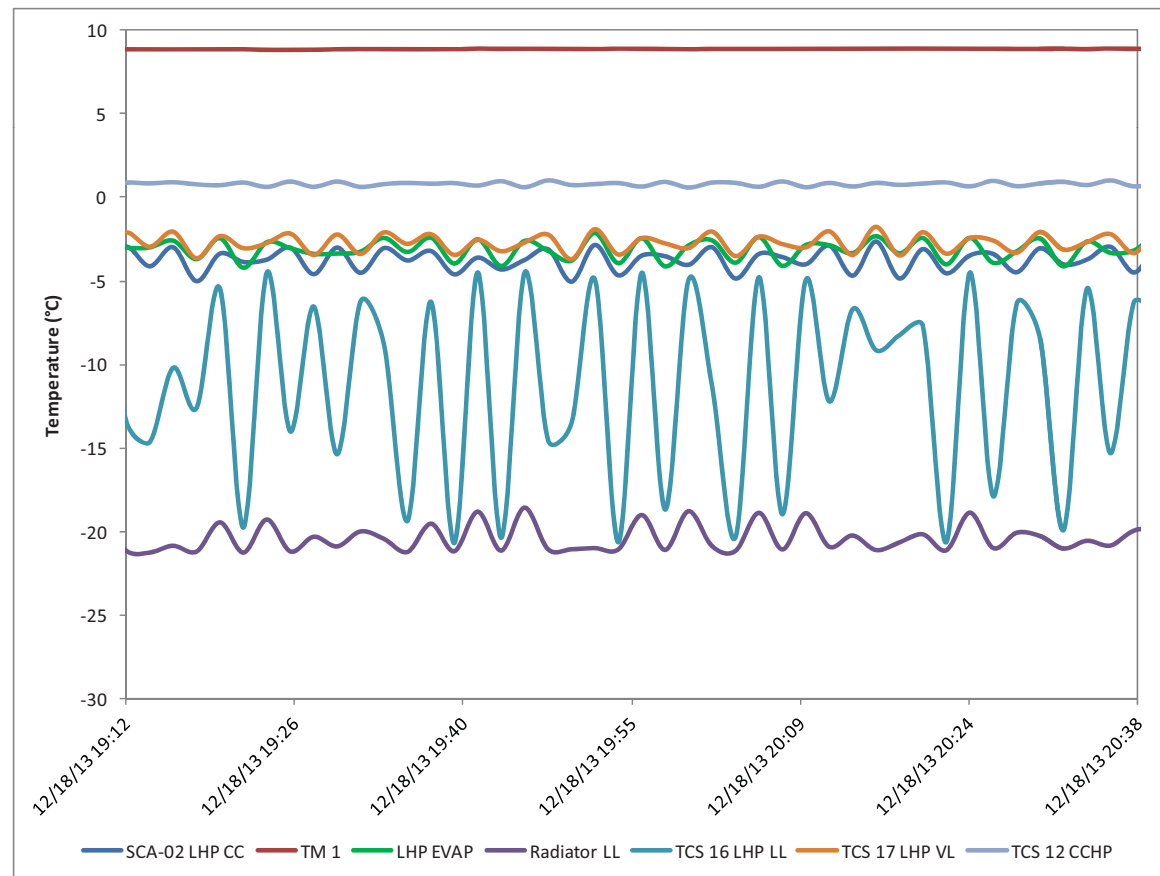


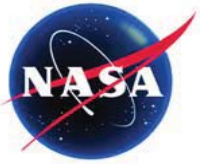


Temperature Oscillation with 38W/19W to Reservoir

- Test #5: Soak
- 38W/19W of control heater power with set points of -2°C/-1°C
- On/off of one control heater (19W) affected the reverse liquid flow.
- Data were collected once every two minutes.

196W to thermal mass 1, shroud at -78°C

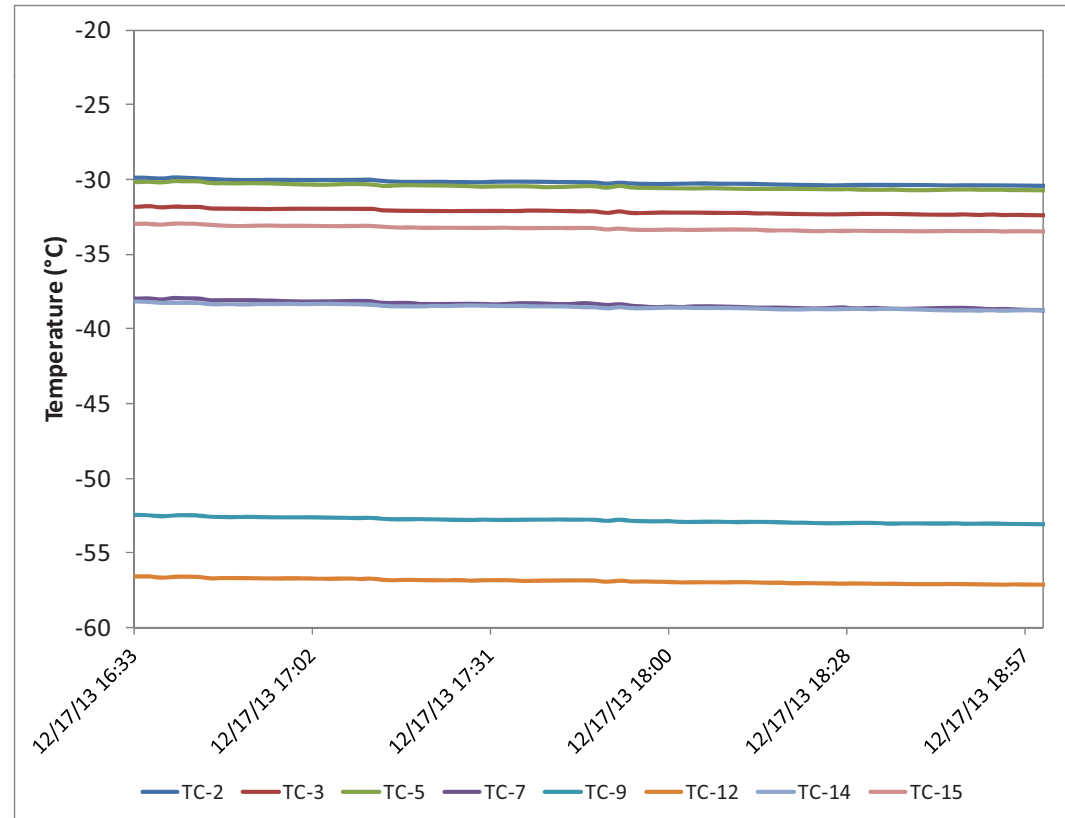


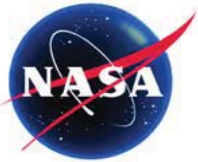


Tracking Vapor Front Movement

- **Test #2: Cold Soak**
- **Data were collected once every two minutes.**
- **Vapor front movement could not be tracked without temperature sensors on the condenser itself. The liquid mass flow rate cannot not be derived.**
- **Reservoir energy balance cannot be verified.**

136W to thermal mass 1, shroud at -101°C, 22W of control heater power with set points of 4°C/5°C

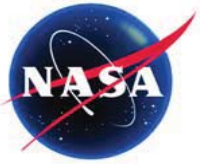




Reservoir Temperature under Various Test Conditions

- Effects of thermal mass power, reservoir heater power, and shroud temperature on reservoir temperature can be inferred from the table.

Test #	Loop Status	Thermal Mass Power (W)	Reservoir Heater Set Points (°C)	Reservoir Heater Power (W)	Chamber Shroud Temperature (°C)	Reservoir Temperature Valley/Peak (°C)
1	Transient	136	+4/+5	22	-101	Decreasing, oscillation
2	Quasi-steady	136	+4/+5	22	-101	-25.0/-22.9
3	Near quasi-steady	196	-2/-1	22	-101	-16.2/-14.2
4	Near quasi-steady	196	-2/-1	22	-78	-8.5/-6.5
5	Near quasi-steady	196	-2/-1	38/19	-78	-4.4/-2.0
6	Transient	196	N/A	0	-78	-20.2 (still decreasing, no oscillation)



Summary and Conclusions

- The high control heater power in ICESat-2 ATLAS LTCS TV testing was caused by persistent temperature oscillation.
- With persistent temperature oscillation, the reservoir was subjected to a repeated influx of cold liquid from the condenser.
- When the reservoir temperature was increasing, reverse liquid flow brought warm fluid from reservoir to condenser.
- The control heater was turned on at all times, but was unable to maintain the reservoir set point temperature due to the additional heat leak to the radiator with persistent temperature oscillation.
- Persistent temperature oscillation was sustained by the combination of gravity assist, reverse liquid flow, and inability of the control heater to maintain the reservoir at the desired set point temperature. Cold radiator temperature and a large thermal mass amplified this effect.
- Causes and effects of persistent temperature oscillation intermingled.
- The theory of temperature oscillation was only partially verified using data from ATLAS LTCS TV testing due to the lack of condenser temperature data. Additional data from past or future LHP tests are needed to fully verify the theory.